STREAMING CLUMPS EJECTION MODEL AND THE HETEROGENEOUS INNER COMA OF COMET WILD 2.
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Introduction: The conventional concept of cometary comae is that they are dominated by fine particulates released individually by sublimation of surface volatiles and subsequent entrainment in the near-surface gas. It has long been recognized that such particulates could be relatively large, with early estimates that objects perhaps up to one meter in size may be levitated from the surface of the typical cometary nucleus [1]. However, the general uniformity and small average particulate size of observed comae and the relatively smooth, monotonic increases and decreases in particle density during the Giotto flythrough of comet Halley's coma in 1986 [2] reinforced the view that the bulk of the particles are released at the surface, are fine-sized and inert. Jets have been interpreted as geometrically constrained release of these particulates. With major heterogeneities observed [3] during the recent flythrough of the inner coma of comet Wild 2, these views deserve reconsideration.

Model: In contrast to release of individual particles, it is modeled that a significant component of the objects are released in the form of aggregate clumps of particulates. These clumps are cemented such that they can disintegrate into their finer constituents long after release. Furthermore, the objects may be ejected by streaming of volatiles through constrained passages to the surface as jets that form distributed sources of secondary particle release with minimal angular dispersion from the surface point of initial release.

Analogies: An oversimplified analog is the familiar artificial firework consisting of a projectile which, after traveling some distance from the point of launch, disintegrates into secondary, then tertiary projectiles. Such a firework is known as a "starburst", and often includes a trail of small particles between splits.

A common experience by investigators who have worked with mixtures of particulate materials with at least one volatile component is that when placed in a vacuum, catastrophic eruptions can result. For example, when using certain powdered minerals to create a martian analog material, it was found during pumpdown to a low atmospheric pressure (10 mbar) that samples of more than a few mm thickness would apparently be stable for many minutes then suddenly erupt violently [4]. This was especially true for mixtures which contained adsorbed volatiles, such as montmorillonites with interlayer H_2O, salts with H_2O of crystallization, and fine-grained chemical powders. To prevent this behavior, it became necessary to thoroughly de-gas the material by thermal bakeout and/or vacuum oven drying for many hours before use [5]. These eruptions typically created a flared conical cavity with a deep core.

Experiments with basalt powders for regolith impact experiments also produced explosive devolatilization, and the potential relevance to planetary phenomena were pointed out [6]. Similar effects have been reported anecdotally for many years by investigators working with powders placed in low-pressure systems.

Investigations into the simulation of interstellar organic synthesis using UV irradiation of volatile material condensed on cryogenic cold fingers have commonly experienced the phenomenon that when such materials are allowed to warm, even slightly, violent volatilization can occur as energy is released in the ice by mobilized and highly reactive ions and radicals [7].

The European artificial comet experiment, known as KOSI, found evidence of release of particles much larger than the inert grains from which the mixture of inert materials and ices was formulated [8].

Mechanisms: Solar insolation is undoubtedly the primary driving energy source for coma formation. However, as the thermal wave penetrates, thermal energy can be converted to stored mechanical energy via a buildup of gas pressure as phase transformations are stimulated in readily volatilized icy constituents. Some phase changes are exothermic, which can further enhance the stored energy. In principle, chemical reactions may be facilitated by the sudden availability of significant amounts of constituents in the highly mobile gaseous form, i.e., homogeneous (gas-gas) and heterogeneous (gas-solid) reactions. In the deep cryogenic state in which they formed and were stored, the diverse chemical constituents of cometary nuclei are almost certainly non-equilibrated, perhaps further augmented by radiochemical stored energy from long-term cosmic ray exposure and the decay of K-40 in minerals.

Cometary material is thought to be fragile and of low tensile strength, based upon the common of occurrence of seemingly spontaneous comet splitting [9] and the observed nature of the final disintegration of comet Shoemaker-Levy 9 under gravity gradient forces as it approached Jupiter. There are many pathways by which deep pockets of gas may eventually find their way to the cometary surface. To the extent that the rubble pile model [10] of small body aggregates is correct, natural seams between cometesimals provide a network of interconnected voids.

After 4.5 billion years of existence, the accumulated pummeling by smaller objects may have created numerous impact channels/tunnels in the near-surface. If hypervelocity impact into low density material produces a conical cavity analogous to the "carrot track" of particles in aerogel [11], it would provide natural channels for release and for light-trapping and focusing of solar energy. In 1974, comet Wild 2 suffered a close encounter with Jupiter [12] that may have created zones of weakness, cracks and crevices in the nucleus.

Trapped gas release can be relatively energetic and violent, with the potential for producing rubble, especially if cometary mixtures are intrinsically physically heterogeneous with natural fracture zones or preexisting voids. Once a passageway become "active" in the release of large material, the production of additional large objects may become self-reinforcing as entrained pieces strike the sidewalls and eject additional aggregates of material. As erosion progresses, pressure-relief driven exfoliation of chunks of material could also be a major contributing mechanism.

Released clumps would be expected to break apart and shed subsequent to their sudden exposure to hard vacuum and solar insolation.. Under these conditions, the more volatile portions of the clumps will be lost to the gas phase by sublimation, the rate being determined by the composition of the volatiles themselves. Extremely volatile materials, like CO-rich ices will sublime rapidly, while H_2O-rich ices and more volatile species trapped in them, will sublime more slowly [13] Even slower sublimation rates may occur if clumps are held together with organic 'glues.' Indeed, experiments in which cometary ice analogs are processed by high energy radiation (UV or particle) demonstrate that complex mixtures of organic species are produced that show a range of sublimation temperatures above that of H_2O ice (200-300K) [14]. In addition to fragmentation driven by volatile loss, shedding also be driven by the release of energy from phase changes and chemical reactions and space charging by solar UV photoelectric effect which could lead to electrostatic disruption. Thus, with mild release velocities, any given clump evolves to a coherent cloud of particles with the height scale for disintegration depending on the nature of the volatiles present and the physical processes in action. At large distances, the outer coma may take on the appearance and characteristics of a more uniform region as the effect of velocity dispersions become prominent.

Evidence: As covered elsewhere [3], the coma of Wild 2 has been found to be remarkably heterogeneous, even at distances of hundreds to perhaps thousands of nuclear radii. Wild 2's trajectory-altering encounter with Jupiter may mean that it is a fresh arrival from the Kuiper belt storage zone [15], and hence that the new thermal environment and minimal surface erosion from only four perihelion passages may be activating highly volatile materials that previously have been stable. Furthermore, if the Wild surface is only now being significantly eroded, accumulated impact zones from its earliest history may be serving as conduits for channeled releases.

It should be asked why the coma of comet Halley was so different. The 4-slope model of the integrated dust fluence during the Giotto passage [2] implies, in fact, at least a bimodal component of dust, which could be a mix between classical dust emission and a clumpy source of larger fragments. From the VEGA flythrough, evidence was given of examples of time-correlated particle densities that were interpreted as particle fragmentation [16]. In addition, the discovery of CN jets from Halley and subsequent examples, has been interpreted [17] as release of volatiles from a distributed source, presumably the CHON particles [18]. Finally, the pulsating jets and the post-perihelion outbursts of Halley and several other comets at large solar distances argue for the presence of buried, but pockets of highly volatile material apparently accessible to the thermal-wave, and the apparent spontaneous splitting of comets are further evidence of intrinsic devolatilization mechanisms for fragility and propensity to disintegrate [9, 19]. The few radar observations of active nuclei made so far typically indicate the presence of cm-size material near the surface. Disaggregation of a single 1 cm particle can produce up to 1E9 particles of 10 um, or 1E12 micron-sized particles.

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